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TITLE: ADVANCED GEOTHERMAL TECHNOLOGIES

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ADVANCED GEOTHERMAL TECHNOLOGIES

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ABSTRACT

Research and development in advanced technologies for geothermal energy production continue to increase the energy production options for the Nation. The high-risk investment over the past few years by the US Department of Energy in geopressured, hot dry rock, and magma energy resources is producing new means to lower production costs and to take advantage of these resources. The Nation has far larger and more regionally extensive geothermal resources than heretofore realized. At the end of a short 30-day closed-loop flow test, the manmade hot dry rock reservoir at Fenton Hill, New Mexico, was producing 10 MW thermal--and still climbing--proving the technical feasibility of this new technology. The scientific feasibility of magma energy extraction has been demonstrated, and new field tests to evaluate this technology are planned. Analysis and field tests confirm the viability of geopressured-geothermal energy and the prospect that many dry-hole or depleted petroleum wells can be turned into producing geopressured-geothermal wells. Technological advances achieved through hot dry rock, magma, geopressured, and other geothermal research are making these resources and conventional hydrothermal resources more competitive. Noteworthy among these technological advances are techniques in computer simulation of geothermal reservoirs, new means for well stimulation, new high-temperature logging tools and packers, new hard-rock penetration techniques, and new methods for mapping fracture flow paths across large underground areas in reservoirs. In addition, many of these same technological advances can be applied by the petroleum industry to help lower production costs in domestic oil and gas fields.

I. INTRODUCTION

Geothermal energy is natural heat in the earth's interior, produced largely by the slow decay of naturally occurring unstable isotopes of uranium, thorium, and potassium. Because the earth's crust is a good thermal insulator, most of this heat is stored at considerable depth below the surface. However, as is true of many insulators between a hot body and its cool surroundings, the rate of increase in temperature with depth--the geothermal gradient--is high, on a worldwide average, about 30°C per kilometer of depth. Therefore, with modern drilling equipment, it is possible almost anywhere to reach crustal rock at temperatures that are usefully high--if not for generating electricity, or, then alternatively, for space heating, food processing, and other direct uses. The reservoir of heat in the earth's crust is one of the largest energy resources that is accessible to man.

Under certain geologic circumstances, meteoric water penetrates the earth deeply enough to reach hot crustal rock. This water extracts heat from the rock, expands, and rises buoyantly where it is trapped in porous formations or natural fractures to form hydrothermal reservoirs of hot water or (rarely) of steam. This hot water or steam can be brought to the surface through drilled holes and used to generate electricity or used for a variety of other purposes.

In the United States, development of hydrothermal resources is growing, and hydrothermal energy is now used to generate 3000 MW of electricity. A comparable amount is generated in other countries. Additional details on hydrothermal resources are provided by Mock and Otte elsewhere in these proceedings. Below, we focus on the geopressured, hot dry rock, and magma resources. In our view, these advanced geothermal technologies could provide significant additional energy resources for our country and the world.

II. SIGNIFICANT ACCOMPLISHMENTS

Geopressured-Geothermal Energy

Geopressured resources are underground reservoirs of hot, pressurized brine that contain natural gas (methane) in solution. In these reservoirs pressures are essentially lithostatic rather than hydrostatic (as in conventional geothermal reservoirs); thus high brine flow rates can be achieved and hydraulic energy can be extracted from the brine at the surface. The potential for combining this hydraulic energy with the thermal energy of the brine and the chemical energy of the natural gas enhances the attractiveness of the resource. The US Department of Energy has supported research on geopressured reservoirs for over a decade to evaluate the technical problems associated with locating, assessing, and producing these resources.

The Geopressured Program has demonstrated that geopressured reservoirs can produce high-volume flows of brine saturated with natural gas over a long time period, and that the gas can be separated and sold (Ramsthaler and Plum, 1987). Solutions to the engineering problems of brine handling and brine disposal have been demonstrated. A six-month flow test of the Gladys McCall well at a flow rate of 24,000-26,000 barrels/day demonstrated that long-term production of a geopressured-geothermal system is feasible (US DOE/EG&G Idaho, Inc., 1987).

Ramsthaler and Plum (1987) state that initial geopressured-geothermal development can occcur where a deep well, initially drilled for gas production, penetrates a geopressured-geothermal reservoir. If the well was originally a dry hole or if the natural gas reservoir eventually played out, then the well could become a candidate for recompletion as a geopressured-geothermal well. Estimates by the Texas Bureau of Economic Geology indicate there are approximately 600 producing wells in Texas drilled through geopressurized-geothermal reservoirs, and the Louisiana Geological Survey has estimated there are a similar number of potential wells in Louisiana. In addition to the natural gas dissolved in the brine, geopressured-geothermal reservoirs can be associated with a gas cap above the brine reservoir. Analysis of logs from the Hulin geopressured well in Louisiana indicates the presence of enough free gas to significantly impact the economics of production from this well. Although the current best-estimate for the saturated gas content of the Hulin brines is 60 ft^3/barrel, the yield of gas per barrel of brine produced could be much higher if there is free gas above the brine reservoir.

To convert an existing deep gas well into a geopressured-geothermal well, it is necessary to recomplete the well in the geopressured brine zones. Although recompletion of a deep well is an expensive operation, the target of opportunity is a very large number of unproductive existing wells in Texas and Louisiana that have access to geopressured-brine reservoirs. If it can be demonstrated that the presence of free gas above these reservoirs can increase the gas yield to 150-200 ft^3/barrel, these wells have the potential to be economic producers at gas prices very close to today's market value (Ramsthaler and Plum, 1987). The economics should improve further if the produced brines, which can have temperatures of the order of 170^oC, are used to generate electricity.

Hot Dry Rock

About 95% of the useful heat in the earth's outer crust is in the rock itself, rather than in any fluid contained in it. Hot dry rock (HDR) technology provides a means to mine this heat in the rock by injecting cold water down one well, into the rock, through natural or manmade fractures, where the heat is conducted to the water, and then extracting the heated water using a second well (Armstead and Tester, 1987). Figure 1 illustrates the HDR concept. The US HDR resource amounts to 90 million megawatt centuries of thermal energy for just the high-grade HDR resources. Research and development programs to develop the HDR technology are well advanced in several countries--particularly in the United States, the United Kingdom, West Germany, Japan, and the Soviet Union. The US work is funded by DOE and is performed by the Los Alamos National Laboratory and by a partnership of Bechtel and Chevron, which is assessing the feasibility of using HDR technology at Roosevelt Hot Springs in Utah.

The world's first hot dry rock geothermal energy system was completed at Fenton Hill, New Mexico, in 1977; enlarged in 1979 by additional hydraulic fracturing; and then operated successfully for more than a year. Water was produced from the manmade reservoir at temperatures and thermal power rates as high as 175°C and 5 MWt. Additional information about the reservoir and reservoir testing is provided by Dash et al. (1983).

Construction of a larger, hotter, hot dry rock system was initiated at Fenton Hill in 1979 to extend HDR technology to the temperatures and rates of heat production required to support a commercial power plant. Two new wells were drilled directionally, one to a vertical depth of 4.66 km, where the rock temperature was 327°C (Figure 2). In December 1983, 21,600 m^3 of water were injected in the deepest well. Details are provided by Dash et al. (1985) and House, Keppler, and Kaieda (1985). Microearthquakes induced by the injection of water indicate seismicity occurred in a 50×10^6 m^3 rock volume. This rock volume is 2000 times greater than the water volume injected. Unexpectedly, the stimulated zone did not propagate into the vicinity of the upper well, and little hydraulic communication between the two wells was achieved. Consequently, in March 1985, the upper well was sidetracked at a depth of 2.9 km and directionally drilled as shown in Figure 2, through the fracture zone created from the lower well. This redrilled well provided the desired hydraulic communication.

In 1986 a closed-loop flow test of the newly completed HDR reservoir was performed to define reservoir operating characteristics so that equipment for a year-long flow test could be designed. Cold water was injected into one of the wells, and the water extracted from the other was as hot as 192°C and produced up to 10 MWt.

Work to date has shown that the HDR geothermal energy concept is technically feasible. The program goal now is to develop the technology to a level that will evaluate economic viability and environmental acceptability.

Operation of the year-long flow test should suffice to observe thermal drawdown and measure long-term characteristics of the reservoir. The test will also provide operation and maintenance experience of an HDR system, thus contributing to future engineering and economic decisions.

Magma Energy

Energy contained in molten or partially molten magma represents a huge potential resource for the US. Smith and Shaw (1975, 1979) estimated this resource within the upper 10 km of the crust to be 50,000 to 500,000 quads--larger than the current estimate for fossil resources. Sponsored by the US DOE and its predecessor agency, ERDA, since 1975, researchers at Sandia National Laboratories are investigating energy extraction from silicic magma systems, which are most representative of magma bodies expected at western US sites. Unlike basaltic magma, the more viscous silicic magma will probably require direct- contact fluid circulation to achieve economic energy extraction rates. Figure 3 (Dunn, 1986) shows a conceptual representation of a single-well, open heat exchanger system. The well is cased into the plastic transition zone, and a concentric inner injection tube extends into the magma. The region surrounding the injection tube is cooled, solidified, and thermally fractured by circulation of the heat transfer fluid. Extent of the fractured zone is controlled by the rate of energy extraction. Beyond the fractured region is a transition zone that behaves like a plastic solid and does not support fracturing. Cooling in the magma zone induces large-scale natural convection that enhances heat transfer to the solidified region.

The magma energy concept was tested in the melt zone of Kilauea Iki lava lake, where an open-hole, sealed test zone was created (Dunn, 1986). During a 5-day test period, energy extraction rates were found to increase with time (indicating growth of the fractured region). Extraction rates reached more than 10 times the expected value for a closed heat exchanger in the same borehole.

The magma program became part of the Department of Energy's Geothermal Program in 1984 after demonstration that energy extraction from active magma bodies was scientifically feasible. The objective of this follow-on program is to assess the engineering feasibility of the magma energy concept and to provide the data base needed for industry to evaluate economic feasibility. Currently, a deep exploratory well is planned for Long Valley caldera in eastern California. The well will be drilled in the southern portion of the resurgent dome within the caldera. If high-temperature, near-magmatic conditions are reached, the well can be used to test newly developed drilling technology, evaluate engineering materials, and confirm heat transfer calculations.

III. CURRENT PROBLEMS AND HIGH-PRIORITY RESEARCH AREAS

Regardless of the nature of the geothermal resources, whether hydrothermal, HDR, geopressured, or magma, many common problems are shared and hence form the basis for key research and development efforts. These problems and the progress toward their solution are described below.

Geothermal Reservoir Engineering

The development and application of computer models for characterizing and evaluating geothermal reservoirs represent a very significant accomplishment and a continuing technology growth area. Over the past decade, the Lawrence Berkeley Laboratory (LBL) has developed a number of sophisticated numerical tools for analyzing the behavior of geothermal reservoirs, interpreting two-phase well test data, and predicting the performance of geothermal fields under exploitation. In recent years, LBL research has focused on the formidable problems associated with fracture- and fault-dominated geothermal reservoirs.

In modeling fracture-dominated reservoirs, special attention must be directed at the coupled geological structure of the field, the dominant role of faults, the complex fluid and heat flow patterns, and the dynamic interaction between the chemical and thermodynamic fluid characteristics. Analysis of the well test data must be made with due consideration for variable fluid temperatures, pressures, and chemistry; two-phase relative permeabilities; and the heterogeneous nature of the fracture-matrix reservoir system.

LBL has completed a successful 5-year cooperative project with Mexico to study the Cerro Prieto geothermal system. This provided an opportunity to test and validate the newly developed reservoir engineering tools and computer models. LBL is currently involved in an analysis of the Ahuachapan reservoir in El Salvador, a reservoir controlled by major faults and fractured porous matrix blocks.

Well Stimulation Techniques

A common practice in the geothermal industry is to complete production wells with slotted liners throughout the production interval of the well. Although initially less expensive, slotted liner completions have the disadvantage of not allowing zonal isolation of productive intervals in the well for future clean up and stimulation treatments. The alternative procedure is to complete the well with a cemented-in liner that is explosively perforated in the production horizons and left intact through nonproductive intervals in the well. This latter completion technique allows periodic treatments to be performed in isolated well intervals without the expense of removing a slotted liner. Reluctance by the industry to accept cemented-in liner completions can be attributed, at least in part, to the questionable performance of explosive jet penetrators in providing the necessary flow communication orifices between the wellbore and the producing reservoir.

The objective of well stimulation is to initiate and maintain additional fluid production from existing wells at a lower cost than either drilling new replacement wells or redrilling existing wells. In geothermal wells, stimulation techniques must be capable of initiating and maintaining the flow of very large amounts of fluid. This necessity for high flow rates represents a significant departure from conventional oil field stimulation and requires the creation of propped fractures with very high near-wellbore permeability and/or fractures with very high flow conductivities over long intervals. The economics of well stimulation will be vastly enhanced when proven stimulation techniques can be implemented as part of the well completion (while the drilling rig is still over the hole) on all new wells exhibiting some form of flow impairment (Hanold and Morris, 1982). This will be particularly true if zone isolation can be achieved through improved well completion techniques.

Under the DOE Geothermal Well Stimulation Program, fractures were created in reservoir formations that produced hot water as a result of matrix permeability and in formations that produced hot water from naturally existing fracture systems. Overall results from this program demonstrated that stimulation is effective where formation damage or locally tight formation zones are present in the reservoir (Republic Geothermal, 1984). Formation damage by invasion of drilling mud and cement is relatively common in both fractured- and matrix-permeability-type reservoirs. Because the damage is normally confined to the near-wellbore area, fracturing or chemical stimulation can be effectively applied. For example, the two fracture treatments performed in East Mesa well 58-30 more than doubled the production rate of this previously marginal producer that contained both a formation-damaged region and a low permeability region in a matrix-type reservoir (Hanold and Morris, 1982).

In fracture-dominated reservoirs, however, the results from stimulation treatments were less consistent. Although production rate increases were always obtained, the increases were not sufficient to convert a poor producer into a commercial well. In hydraulic fracture treatments conducted at Raft River, Idaho, and Baca, New Mexico, extensive highly conductive fractures were created and propped, but they failed to establish commercial productivity from marginal reservoirs. It is suspected that these fractures may have paralleled the predominant natural fractures in the formation and failed to effectively connect them with the wellbore. Results from this well stimulation program suggest two approaches for future stimulation treatments in fracture-dominated reservoirs:

(1) In the fracture treatments performed at Raft River and Baca, large hydraulic fractures were initiated in nonproductive well intervals. A more promising approach would be to focus on stimulating existing productive fractures to take advantage of the phenomenon of "fracture compliance." Natural fractures are known to dilate during fluid injection and to constrict during production with a corresponding loss in productivity. For an elastic or compliant fracture system, it should be possible to prop fractures in the dilated state, thus retaining a higher fluid conductivity under production conditions (Republic Geothermal, 1984).

(2) New stimulation techniques capable of driving multidirectional fractures that have a high probability of intersecting nearby natural fracture systems would be a significant technological advance. The use of a propellant or gas-generating stimulation concept should be investigated for this purpose. Sandia National Laboratories has investigated high-energy gas fracturing as a technique for creating multiple fractures in a geothermal well.

Relative to other technology development work, effective well stimulation treatments continue to offer one of the greatest potential opportunities for enhancing the economics of geothermal power production.

Fracture Mapping

Determining the orientation and location of fractures along which water flows during hydraulic fracturing is of major importance in all geothermal reservoirs. A successful method developed at Los Alamos to accomplish this involves locating and analyzing microearthquakes that occur during the hydraulic fracturing operations that are carried out either to create the reservoir, as in the HDR case, or to stimulate conventional hydrothermal reservoirs. The microearthquakes occur as a direct result of fluid injections; therefore, their locations may indicate the location of flow paths. The procedure for monitoring and locating the microearthquakes has been described by House (1987), and new techniques developed by Fehler and others (1987) reveal the geometry of the fracture system along which the water flowed and microearthquakes occurred. Although this new fracture mapping technique was developed specifically for HDR reservoirs in crystalline rock, the techniques should also work in the sedimentary rocks in which the oil and gas industry conducts hydraulic fracturing to stimulate improved productivity.

Monitoring Reservoir Heat Depletion with Chemically-Reactive Tracers

Temperature-sensitive, chemically reactive tracers have been developed at Los Alamos to map the progress of the thermal front accompanying heat extraction from HDR and those hydrothermal reservoirs that utilize reinjection of the spent, cold geothermal production fluids. When the cold front associated with the reinjected fluid reaches the production well, the temperature there will decline precipitously, signifying the end of useful heat extraction. Because of the strong temperature dependence of reaction rate with temperature, a series of reactive tracer experiments in which extent of reaction is measured provides a measure of the rate of advance of the thermal front, thus giving advance warning of the onset of severe thermal decline.

The chemical reaction kinetics for two families of reactions has been studied: the hydrolysis of organic esters and amides, and the hydrolysis of aryl halides. The esters and amides appear to be promising tracers for low-temperature reservoirs in the range of 75^o - 100^oC, and the aryl halides are more appropriate in the temperature range of 150^o - 275^oC. Preliminary adsorption studies for the aryl halides indicate a small propensity to adsorb on granitic rock, but the amount of adsorption should not adversely affect the use of the tracers. Future laboratory work is required to examine the adsorption issue more closely, as well as to develop a sensitive analytical technique for measuring the expectedly small tracer concentrations. The culmination of the reactive tracer experiment will be the field demonstration in the Fenton Hill reservoir during the upcoming long-term flow test.

Hard Rock Penetration

Drilling and well completion are difficult in most geothermal reservoirs and represent the major cost in developing geothermal resources. To address these problems, Sandia National Laboratories is conducting research and development in borehole mechanics and rock penetration mechanics. The borehole mechanics task addresses problems in lost circulation control and drilling fluids. A large, high-temperature lost circulation test facility has been constructed, and comparative data on materials performance have been generated. With Texas Tech University, Sandia has evaluated bentonite and bentonite/saponite mixtures for use as geothermal drilling fluids. Rock penetration mechanics research resulted in the introduction and acceptance of polycrystalline diamond compact bits. A joint Sandia/industry development of a computer code for analysis of drill string dynamics has recently been completed. In addition, drill strings for operation in very high temperature formations are being designed.

Borehole Logging and Well Completion Equipment

Borehole tools originally developed at Los Alamos have been used to transmit seismic signals between wells at unprecedented rates and numbers. An acoustic source transmitter scans a section of one wellbore, while a receiver is stationed in an adjacent wellbore. The receiver consists of a piezoelectric transducer that is tuned for maximum response at the transmission frequency. The characteristics of the medium through which the acoustic vibrations pass are deduced from the character of the received signals and from their arrival times at the receiver. The distance between two boreholes can be measured with great accuracy, and the presence of fluid-filled fractures in the formation can be determined.

A high-temperature, downhole fluid sampler was developed to provide borehole fluid samples of 4 liters. This sampler was used during the Salton Sea drilling program to retrieve samples in fluids where the borehole temperature exceeded 350°C.

Developments in wellbore diagnostics at Sandia National Laboratories have included high-temperature electronic components, a wellbore navigator, and cement bond logging tools. Recently, dewared "slickline" tools with downhole memory were developed for pressure, temperature, and flow measurement. A prototype borehole radar tool with directional capability has been designed and assembled. The instrument is designed to locate producing fractures up to 100 m from the wellbore. The prototype is being evaluated and upgraded in a series of laboratory and field tests.

An open-hole packer system was designed, fabricated, and tested by Los Alamos and Baker Production, with US DOE funding. The system shown in Figure 4 has been used to isolate zones, to conduct injection tests, and to stimulate HDR reservoirs as hot as 260°C. After exposure to temperatures of 240°C, the packer has functioned at differential pressures up to 40 MPa (5500 psi). Three high-pressure, massive hydraulic fracturing operations, each injecting over 3800 m^3 of water, have been conducted using the packer system.

IV. TECHNOLOGY SPINOFFS

In the past, much of the technology needed for geothermal development came from the oil and gas well drilling industry. Recently, however, under DOE and other sponsors of geothermal development programs, numerous technology advances have evolved or been identified that could find direct application in the extraction of petroleum and natural gas resources. For example, new techniques in well stimulation described above could be used to increase production in stripper wells. The microseismic technique for mapping fracture flow paths has been identified by representatives of the oil industry as a critical area of technology. Application would be in stimulation treatments and during enhanced oil recovery reservoir treatments. New logging tools such as the fluid sampler and radar tool could find application in petroleum reservoirs where existing tools are inadequate. For example, in steam drive fields and some high-temperature development wells (e.g., 250°C wells in Texas), these tools could be useful. Diagnostics are required to evaluate the effectiveness of current steam flood and fire flood operations.

V. CONCLUSIONS

Recent advances in geothermal technology and concepts have moved geopressured, hot dry rock, and magma energy closer to the point of economic viability. These new technologies for producing geothermal energy can tap a vast geothermal energy resource within the US and elsewhere in the world. Questions about cost and technical feasibility remain. Research and development in these advanced concepts have produced numerous technological advances. These technological advances include new hardware, new methods, and new concepts for geothermal energy extraction. All contribute to enhancing the economics of geothermal production. Moreover, many of these same technologies can be applied to the petroleum industry and can provide a means for extracting additional oil from domestic reservoirs that would otherwise be considered depleted.

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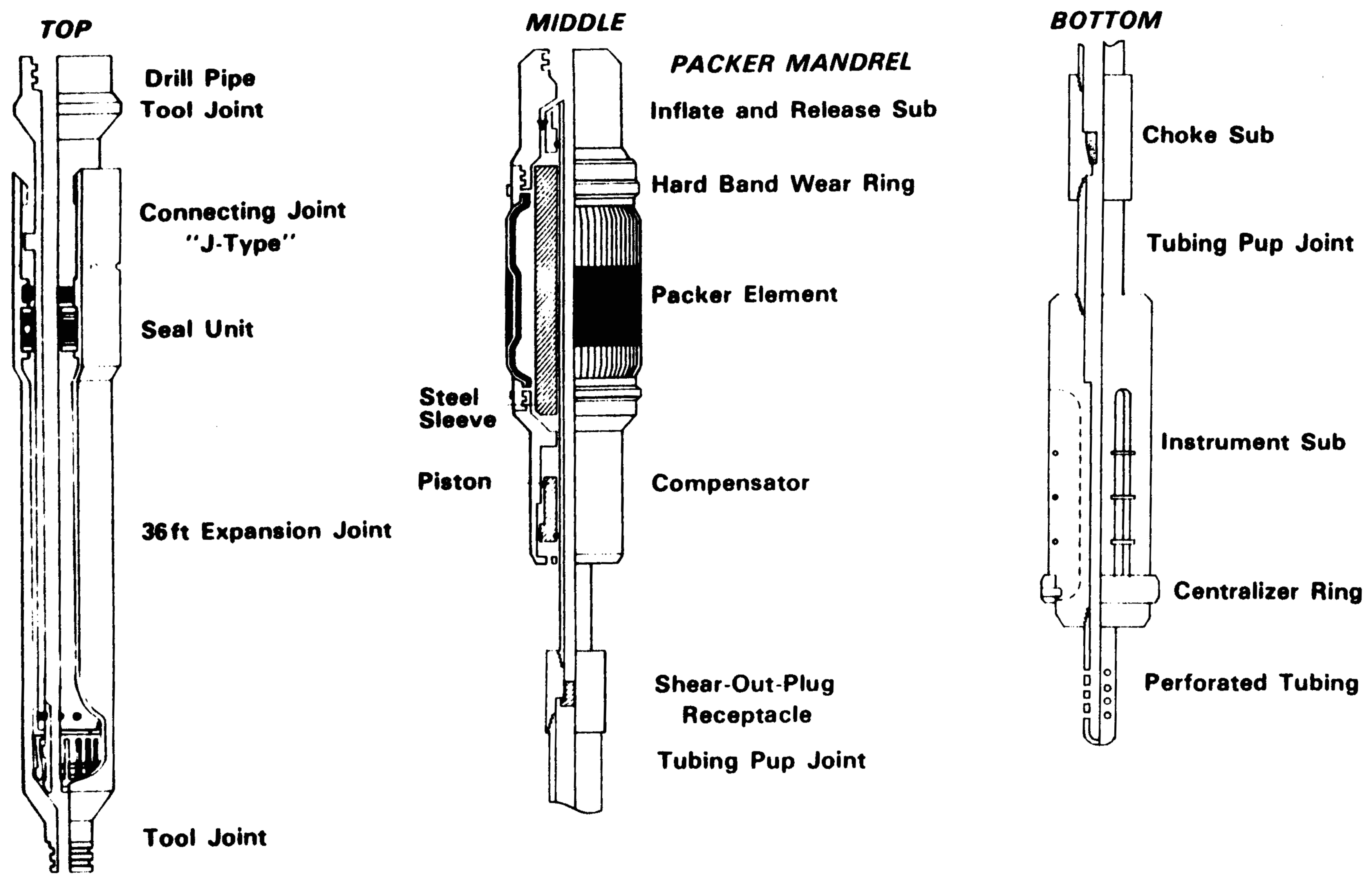
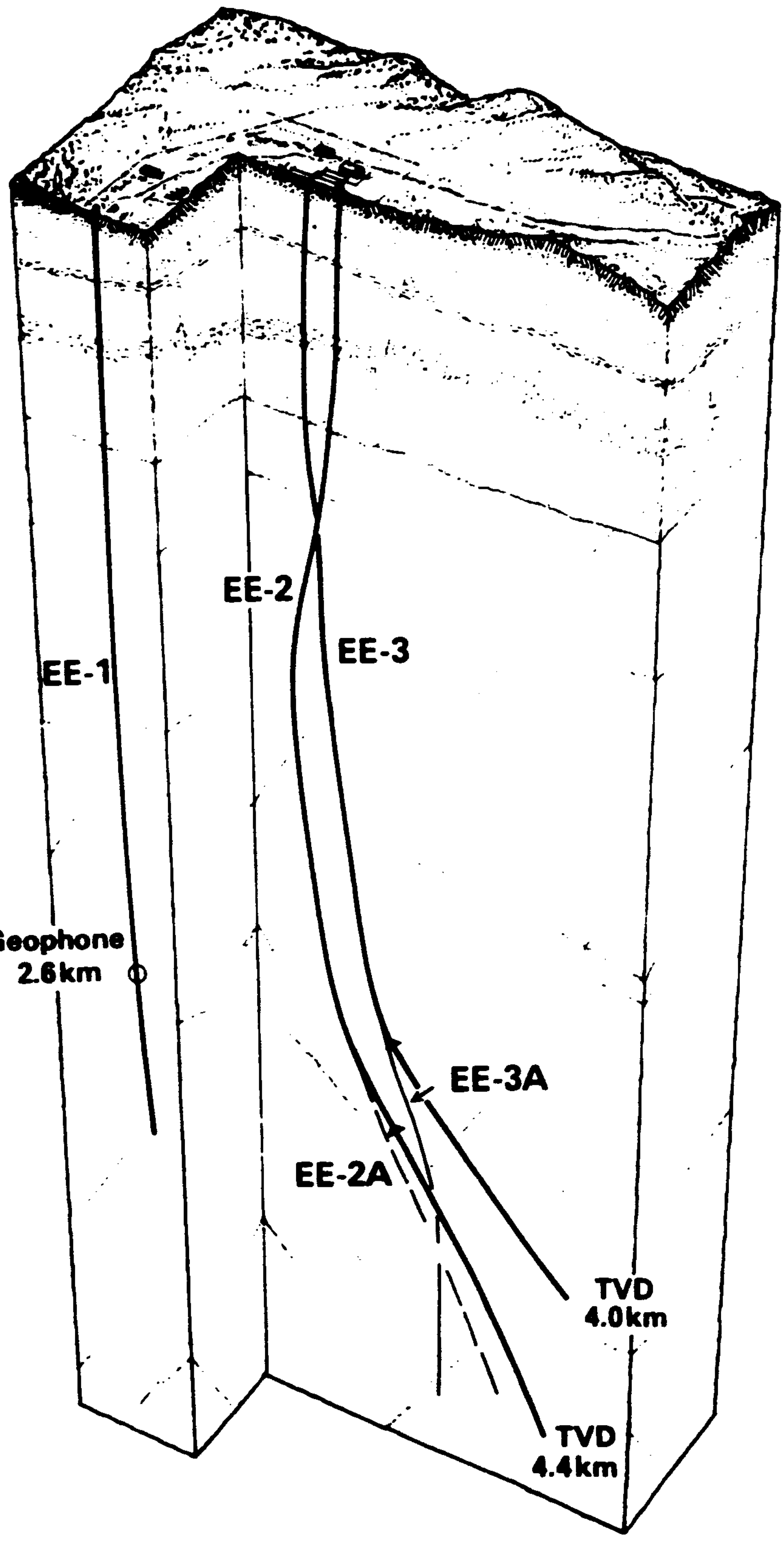


A. EXPANSION JOINT

B. PACKER AND COMPENSATOR

C. CHOKE AND INSTRUMENT SUB

OPEN HOLE PACKER ASSEMBLY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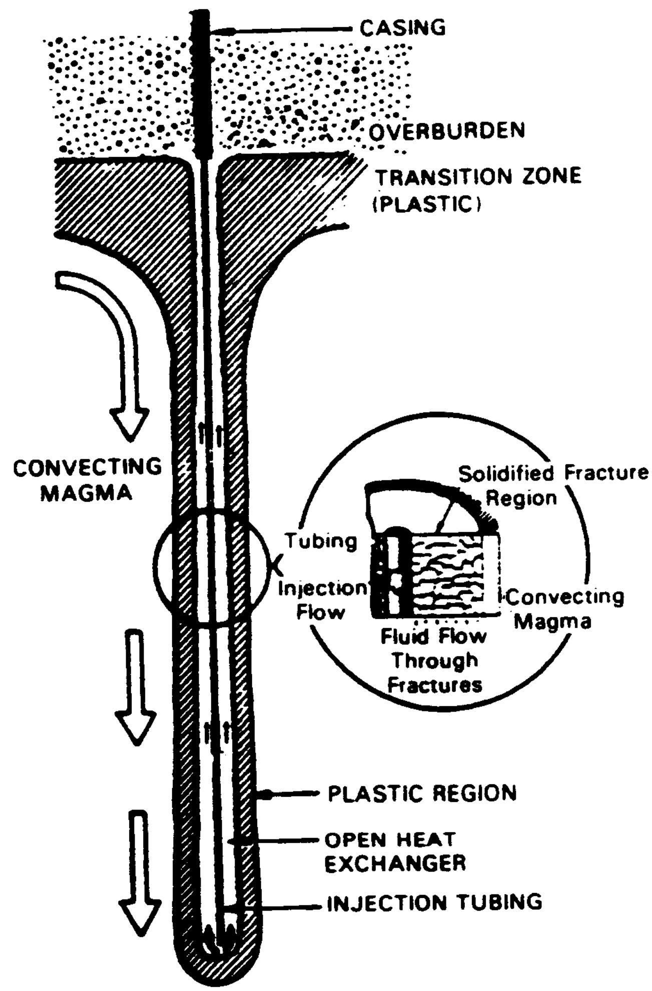
EE-2
EE-3
Geophone
2.6km
EE-3A
EE-2A
TVD
4.0km
TVD
4.4km


CASING
OVERBURDEN
TRANSITION ZONE
(PLASTIC)
CONVECTING
MAGMA
Solidified Fracture
Region
Tubing
Injection
Flow
Convecting
Magma
Fluid Flow
Through
Fractures
PLASTIC REGION
OPEN HEAT
EXCHANGER
INJECTION TUBING